Eutrophication of Tenkiller Reservoir, Oklahoma and Effects on Water Quality and Fisheries

Expert Report of Dr. G.D. Cooke and Dr. E.B. Welch

for

State of Oklahoma

in

Case No. 05-CU-329-GKF-SAJ

State of Oklahoma v. Tyson Foods, et al.

(In the United States District Court for the Northern District of Oklahoma)

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- The switch to eutrophic-hypereutrophic trophic states in Tenkiller produced major changes in water quality. These changes presently endanger human health and the environment. There were shoreline scums of algae and reduced water clarity, especially in upper reservoir areas. Dominant algae became blue-greens (Cyanobacteria), which were associated with disinfection by-products, tastes, and odors in treated tap water, and produced a human liver toxin (microcystin) found in Tenkiller in 2003.

- Drinking water produced by utilities along Tenkiller's shoreline was negatively affected by its eutrophic state. Tenkiller water is rich in organic matter produced by reservoir algae and brought in by the river. Disinfection with chlorine in drinking water utilities produced carcinogenic and embryo-toxic by-products, mainly chloroform and other trihalomethanes, which occur when chlorine is mixed with organic matter-rich Tenkiller water. Commonly 20-30% of tap water samples from Tenkiller water had disinfection by-products in excess of USEPA standards. Eutrophication of Tenkiller produced human health risks. A potable water utility on the Illinois River also had elevated disinfection by-products in finished tap water. Objectionable tastes and odors appeared in some Tenkiller tap water.

- Tenkiller is at risk for continued problems with algae, including episodes of tastes and odors, production of disinfection by-products and algal toxins, and areas of low and zero DO, this will occur because Tenkiller TP appears to be increasing.

- Broken Bow was eutrophic in 1997, but oligotrophic-mesotrophic in 1995 and 2001-2007. Broken Bow's low amount of algae and clear water occurred because TP in inflows was low, leading to low reservoir TP concentrations.

- The mean TP concentration of river water to Tenkiller was 5 times higher than Broken Bow's. This is why Tenkiller is eutrophic-hypereutrophic and Broken Bow is oligotrophic-mesotrophic. The difference in river TP concentrations is from different land uses in the watersheds. Broken Bow's watershed is 79% forested, Tenkiller's is 43% forested and 45% is in pasture. Currently, pastures of Tenkiller's watershed are used for disposal of about 354,000 tons of poultry waste per year, and runoff from them yields 59% of the TP load to Tenkiller.

- Fifty year model simulations indicate Tenkiller's trophic state in the deep, open water areas (LK-01 and LK-02) may be moved to mesotrophic-oligotrophic condition at the end of a fifty year period, if TP concentrations in inflowing waters are significantly and permanently reduced through cessation of poultry waste disposal. The upper reservoir station LK-04 may move to eutrophic conditions after a fifty year period, while LK-03 may become mesotrophic. Large quantities of TP have been deposited in Tenkiller sediments since poultry waste disposal began. This TP may become available to algae through recycling, delaying reservoir recovery after cessation of poultry waste disposal. If poultry waste disposal continues and grows at the current rate, the model projects TP increases leading to greater eutrophic states at LK-01 and LK-02, and hypereutrophic states at LK-03 and LK-04. Large entire-summer algal blooms with attendant water quality problems (including human health risks and worsened fish habitats) are likely.

B. Opinions and Conclusions of Dr. Eugene B. Welch

Dissolved oxygen (DO) is an important water quality constituent that is strongly affected by eutrophication. The eutrophication-caused degraded DO regime in Tenkiller adversely affects production and ultimately sport catch of cool water fish species that are endemic to, as well as stocked in Tenkiller. Of special note are Smallmouth bass (SMB), walleye and striped bass. This adverse effect is due to the restriction of suitable habitat during the thermally stratified period in summer when DO declines to less than 2 mg/L in over 70 percent of the deep lacustrine water column, violating Oklahoma's water quality standard. More definitively, the volume with temperature and DO levels that are optimum for growth (< 27°C, > 6 mg/L) of SMB, a species known to be intolerant of eutrophication, is largely absent and/or very restrictive. Habitat restriction was similar for even suboptimal growth (< 29°C, > 5 mg/L). Prevented from accessing cooler metalimnetic and hypolimnetic water, because of lethal DO levels, fish were forced to survive in the epilimnetic water with adequate DO, but with temperatures too high for optimal or suboptimal growth.

That this DO/temperature regime in eutrophic Tenkiller adversely affected SMB production is supported by significantly higher catch rates in Broken Bow, which is oligo-mesotrophic and comparative in area and depth, but without the restrictive DO/temperature regime as in Tenkiller. SMB is a highly desired game fish species due to their exceptional fighting character when hooked. That is supported by the stocking effort in the 1990s by ODWC to establish a sustainable population and catch of this highly desired species in Tenkiller. Broken Bow was also stocked, but earlier in the 1970s-1980s. Clearly, SMB thrives more in oligo-mesotrophic Broken Bow than in Tenkiller.

The DO/temperature habitat restrictions in Tenkiller are even more severe for introduced walleye, which also have significantly higher catch rates in Broken Bow. Essentially, not even suboptimal conditions for walleye were available for much of the summer in Tenkiller due to the more restrictive temperature requirements of walleye.

Introductions of striped bass have failed in Tenkiller, probably due to the DO/temperature regime, which is as restrictive as that for walleye. The likely adverse effect of Tenkiller's restrictive DO/temperature regime on striped bass is well supported by results from other reservoirs.

Reversal of this condition of poor habitat for these sensitive species will be slow and incomplete if application of poultry waste in the watershed ceases (Wells, 2008). Even if inputs from poultry and domestic wastes were still at historical levels that existed at dam closure, habitat improvement would be modest compared to current levels (Wells, 2008). Only if TP input had remained at near natural levels would available habitat be much greater (Wells, 2008), and similar to oligo-mesotrophic Broken Bow. Continuing to increase poultry waste application at the current rate would maintain the near worst-case DO/temperature habitat availability.

The adverse effect of low DO in Tenkiller is also demonstrated by low abundance of bottom invertebrates, compared to that in Broken Bow, despite the probable greater food supply resulting from higher production in eutrophic Tenkiller. The poor DO habitat for bottom fauna is indicated by the high anoxic factor (AF=days with < 2 mg/L DO), which is much greater than the hypereutrophic boundary value.

The unsuitable DO conditions for aquatic life in Tenkiller, compared to Broken Bow, are due to the greater loading of total phosphorus (TP) to Tenkiller, which is several-fold above the "excessive" boundary for lakes. Higher TP loading translates into higher TP concentration, higher algae concentration and lower meta and hypolimnetic DO, due to higher DO deficit rates (AHODs). This is supported by the much higher observed TP, algae (chl) and AHOD in eutrophic Tenkiller than in oligo-mesotrophic Broken Bow. The difference in the trophic states of these two reservoirs is due to observed spring-summer TP inflow concentration that is 6 fold greater to Tenkiller. The effect of greatly reduced TP loading (i.e. natural) is clearly shown by model simulation (Wells, 2008).

These injuries due to low DO, which are caused by high TP loading, are currently endangering fish and aquatic life.

The TP loading to Tenkiller has more than doubled since the first decade after dam closure, due largely to poultry waste spreading in the watershed (Engel, 2008). That observation is supported by the relationship between calculated P deposition rate, determined from dated sediment cores, and data on poultry production (Fisher, 2008). Although poultry waste was being applied during the first decade after dam closure, estimated inflow TP at that time of about 100 μg/L was still less than one half the current (1997-2004) observed inflow concentration (227 μg/L). Had poultry waste not been applied and domestic waste water not been discharged to inflowing waters, the natural background inflow TP may have been nearer 20 μg/L, which would have produced an oligotrophic state in Tenkiller, similar to that of Broken Bow.

II. INTRODUCTION

A. Purpose

This report summarizes past and recent findings on cause(s) and effects (injuries) of eutrophication in Tenkiller Reservoir, Oklahoma (Tenkiller). Excessive loading of phosphorus (P), along with associated organic matter, are the causes for eutrophication and associated water quality degradation. The principal source of P to Tenkiller is from poultry waste applied to pastures and leached to receiving streams during runoff, eventually reaching the Illinois River, Baron Fork, and Caney Creek and then reaching into Tenkiller.

The cores were sectioned at 2-cm intervals to depths of 38-54 cm within 24 hours of collection. Sections were analyzed for water content and TP according to EPA methods 3050 and 6020 (Fisher, 2008).

Sedimentation rates were determined over an approximate 50-year period, from reservoir construction until 2005, by dating each sediment section using ^{137}Cs and ^{210}Pb procedures. Analyses were performed by Prof. F. M. Soster, DePauw University, who used the Constant Initial Concentration (CIC) Model for unsupported ^{210}Pb (Fisher, 2008).

Deposition of P over time was calculated from the dry matter content of TP (mg/kg), the fraction of dry matter in each time-depth interval, and corrected for TP retention (0.83), based on whole reservoir TP concentrations observed during 2006, to approximate annual TP loading.

The data used in this report are considered adequate to support the conclusions. A complete description of all field and laboratory sampling and analytical procedures and methods is provided in Sections 2.11 and 2.12 of Olsen (2008).

V. RESULTS AND DISCUSSION

A. Disinfection By-Products in Tap Water from Utilities along the Illinois River and Shores of Tenkiller [1]

Disinfection by-products (DBPs) are formed as raw reservoir or river water is disinfected with chlorine (Teaf, 2008). DBPs occur when chlorine reacts with dissolved organic molecules (e.g. lignins, humics, algal extracellular products) in the untreated water. These organic molecules in the untreated water are called DBP precursors. Trihalomethanes (THMs; e.g. chloroform, bromodichloromethane) and haloacetic acids (HAA5s; e.g. dichloroacetic acid, trichloroacetic acid) are among the most common DBPs. The term HAA5 means that there are 5 haloacetic acids that are combined into one value for reporting. DBP precursors in reservoirs are directly linked to the eutrophication process through total and dissolved organic carbon (TOC and DOC) drainage from the watershed and TOC-DOC production by algae in the river and reservoir.

The U.S. Environmental Protection Agency (USEPA) established threshold concentration values for DBPs in finished tap water (USEPA, 2005, 2007) because DBPs pose human health risks. DBPs are linked to cancers of the bladder, rectum, and colon, and to increased incidences of stillbirths (USEPA, 2003; King et al. 2000). The increased risks of bladder and rectum cancers are well-documented (Morris et al. 1992; Villaneueva et al. 2007). Presently, the threshold concentrations are 80 µg/L for THMs and 60 µg/L for HAA5s. Tap waters with concentrations above these thresholds are in violation of USEPA standards. Because health risks may be dose-dependent, "near-violations" (a

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[1] Dr G.D. Cooke is the primary author of this section.

term developed for this report) are considered to be DBP concentrations 10 percent or less below the USEPA thresholds. Thus THM concentrations of 72-79 µg/L in tap water, are "near-violations" of the guidelines, and may pose human health risks near that of the threshold violation value of 80 µg/L.

Utilities may employ pre-chlorination or post-chlorination treatments of water to lower precursor concentration or formed DBPs. These treatments include aluminum sulfate coagulation of raw water and/or sand or activated carbon filtration of chlorinated water. Costs per unit of finished tap water are high for smaller (number of customers) utilities (Walker, 1983). Because of its potential cost-effectiveness, the American Water Works Association Research Foundation, as well as many other scientists (e.g. Stepczuk et al. 1998 a, b), advised utilities to attempt to lower DBP precursors in raw water by reducing precursor production in the watershed (e.g. wetland and agricultural runoff) and by reducing algae production in eutrophic reservoirs (e.g. Cooke and Carlson, 1989; Graham et al. 1998). Algae production is strongly linked to P loading from the watershed and P concentration in the reservoir water (see Section C, Reservoir Trophic State).

Sources of DBP Data for Tenkiller and Illinois River Utilities

There are 4 potable water supply utilities along the streams of the Oklahoma portion of the Illinois River watershed and 14 along the shores of Tenkiller. Some of them have less than 200 customers. The largest utilities are the towns of Tahlequah, OK (18,431 customers), located on the Illinois River, and Sequoyah County Water Association (15,719 customers), located near the reservoir's dam and reservoir sampling station LK-01 (Figure 3).

The small treatment plants (< 200 customers) reported DBP concentrations to the Oklahoma Department of Environmental Quality (ODEQ) from a single yearly sample. The larger utilities reported DBPs to ODEQ on a quarterly basis. These reports to ODEQ (Appendix A; compiled by HSWMR Inc.) are the basis of the following description of DBPs in the tap water of the utilities along the Illinois River and Tenkiller.

CDM sampled DBP concentrations within the communities served by the Gore PWA, Cherokee County RWD #2, and Tahlequah PWA, during summer 2006. These data are described separately from the ODEQ data. The CDM samples were taken by CDM personnel, accompanied by each water plant manager, at locations that correspond to locations regularly sampled by plant personnel. Each location was confirmed to have no interfering processes operating at the time of sampling (e.g. aerators, water purifiers), and samples were taken after allowing faucets to run for periods consistent with each plant manager's sampling techniques. Samples were sent to Alpha Woods Hole Laboratory, priority overnight, packed in ice, under chain of custody.

Results of the Tap Water Disinfection By-Products Survey

Locations of the 18 drinking water treatment plants in the Oklahoma portion of the Illinois River watershed streams and along the shores of Tenkiller are shown in Figure 3. These utilities are also listed in Table 1 and Appendix A, along with the period of sampling and reporting record at ODEQ, the number of samples, and the number of violations and near-violations for the period of record. Table 2 is a list of the DBP data obtained by CDM in 2006 for Cherokee County RWD #2, Gore PWA , and Tahlequah PWA.

Fin and Feather Resort (Tenkiller), Adair Co. RWD #5, and Flint Ridge (Illinois River) did not report DBPs in their tap water over an 8 year span (Table 1).

The other 15 utilities reported DBPs (THMs and HAA5s) in tap water, with THM violation and near violation frequencies ranging from 0 percent of samples (LRED Wildcat) to 33 percent of samples (Burnt Cabin RWD). The highest numbers of HAA5 violations and near-violations were at GORE PWA (8) and Tahlequah PWA (11) (Table 1).

Utilities with 15 or more reports to ODEQ over the 8 to 10 years of reporting may give a more accurate picture of DBP violation frequency. Flint Ridge (17 reports), had no THM or HAA5 violations or near-violations. At the other utilities, THM violation frequencies of 10 percent to 20 percent of samples were common, ranging up to 36 percent (Tenkiller Water Utility Company, Burnt Cabin RWD). When occurrences of HAA5s in tap waters of the utilities with higher reporting frequencies are included, violations and near-violations of 20-30 percent or more were found (Table 1).

The Sequoyah County Water Association (15,719 customers) has a raw water intake located near reservoir sampling station LK-01 and the dam (Figure 3). With 64 reports between September 1999 and January 2008, 25 percent of tap water samples were contaminated with THMs, above or near the violation threshold. There were 13 percent actual THM violations and no HAA5 violations or near-violations (Table 1).

The Cherokee County RWD #2 had two THM violations and one near violation during summer 2006 (samples from a grocery store and a home), and Gore PWA had 2 near-violations in tap water during that summer (CDM data, Table 2).

The City of Tahlequah, OK (18,431 customers) obtains its raw potable water from the Illinois River. Tahlequah PWA reported an increasing frequency of THM and HAA5 violations to ODEQ (Table 3). Between February 1997 and December 2007, 148 tap water samples were analyzed. Three dates were sampled by CDM in 2006 (Table 2). There were 4.7 percent to 6.7 percent violations and near-violations of the THM and HAA5 thresholds over the almost 11 year span of reporting by Tahlequah PWA. In the 8 year period from February 1997 to March 2005, THM and HAA5 violations and near-violations were lower (1.8 percent to 5.4 percent) than the 11 year frequency. There was a rate of 0.97 THM violations and near-violations per year during this 8 year period. Violations and near-violations increased between June 2005 and December 2007 (Figure 4). There were THM violations in 16 percent of the 50 samples in that period, a rate of 5.3 THM violations and near-violations per year. All violations occurred during June and August (Table 3). The CDM samples of the Tahlequah tap water during summer 2006 found 40 percent THM violations or near-violations and 27 percent HAA5 violations or near-violations. The CDM samples were taken at sites in the distribution system, including grocery stores and the wastewater treatment plant water fountains (WPC Plant) (Table 2).

Discussion of Disinfection By-Product Survey Results

Total trihalomethane formation potential (TTHMFP) is a measure of the potential of a reservoir or lake water sample to form THMs when chlorinated. It is a method to evaluate raw (untreated) drinking water for the presence of THM precursor molecules such as those that are produced by algae or transported to the reservoir from land runoff or from synthesis by river algae. The water sample is treated with enough chlorine to achieve a chlorine residual of at least 3 mg/L at the end of a seven day incubation period under standard conditions. At this point, the sample is tested for THMs (APHA, 1992; USEPA, 1998). TTHMFP samples from Tenkiller were taken at a 3 meter depth near raw water intakes.

The appearance of DBPs in tap water is causally linked to eutrophication of the water supply. Palmstrom et al. (1988) demonstrated that THMFP increased as water moved along the length of a eutrophic Ohio water supply reservoir. Not only were DBP precursors added to this reservoir by the river, but one-third of the total precursors entering the potable water supply treatment plant were produced in the reservoir itself. Their studies, along with those of Wachter and Andelman (1984), Sondergaard et al. (1985), and many others, demonstrated that algae in the reservoir (live cells and algal extracellular products, ECPs), were significant sources of THM precursors.

These observations and conclusions strongly supported the detailed study of the origins of THM precursors in the reservoir waters that supply New York City (NYC). THMFP was significantly correlated with TP and TOC concentrations in the reservoir, and algal blooms were significantly correlated with TP concentrations. Blue-green (Cyanobacteria) blooms were associated with the highest THMFP. The NYC water supplies were strongly and adversely affected by non-point runoff, including livestock operations (Stepzcuk et al. 1998 a, b).

High TOC and DOC concentrations in the water are strong indicators of the presence of THM precursors (Walker, 1983). The sources of TOC and DOC in Tenkiller are inflowing river water and production by algae and microbes in the nutrient-rich waters of the river and reservoir. TOC in the reservoir averaged 2.5 mg/L, vs. 1.5 mg/L in the inflowing water (Olsen, 2008). The additional TOC in the reservoir was produced by its algae. As shown in the Trophic State Section of this report (Section C), production of algae and thus the production of TOC and DOC is driven by the inflows of TP into Tenkiller from the watershed (Engel, 2008; Wells, 2008). The major sources of TOC and DOC in the Illinois River are from algal production in the river itself, driven by the high TP concentrations in its water, as well as from land runoff from poultry waste land applications and from domestic waste. The TOC concentration in water draining off poultry waste-amended pastures had a median value of 10 mg/L, versus the median concentration in runoff from the non-amended pastures of 1.0 mg/L (Olsen, 2008). The area of wetlands on the watershed is < 1 percent (Homer et al. 2004), indicating that wetlands are not important watershed sources of TOC and DOC.

TOC and DOC concentrations in Tenkiller surface waters were determined in summer 2006 by CDM (Table 4). Average DOC concentrations were between 2.35 and 2.47 mg/L at the four sampling stations in Tenkiller, with a range of 1.0 to 5.5 mg/L. The relationship between TOC and THMFP in Tenkiller (summer 2006 and 2007 CDM data; Table 5) is significant ($r = 0.59$, $p < 0.05$) (Figure 5). As TOC increased in Tenkiller, the risk by utilities along it to produce THMs in tap water increased.

Table 6 is a list of the results of the TTHMFP survey at 9 potable water utilities along Tenkiller's shores (see map, Figure 3). Results are presented as maximum, minimum, and average TTHMFP, along with the number of samples. Cherokee County RWD #2 and #13 and Gore PWA had between 1000 and 2000 customers, whereas the other utilities in Table 6 were much smaller (see Table 1 for customer numbers).

All nine utilities had a THMFP in excess of the THM violation standard of 80 µg/L set by the USEPA. This means that their untreated Tenkiller water had to be treated (e.g. flocculation, filtration, activated carbon) to remove THM precursors found in the DOC of the reservoir water. Their successes at removal are listed in Table 1. Of the nine utilities in this study, only LRED (Wildcat) and Fin & Feather reported 0 percent THM in finished tap water. In the others, 11 percent to 33 percent of the finished tap water samples (Table 1) were contaminated with carcinogenic THMs above the USEPA violation threshold. They were incompletely successful in removing THM precursors prior to chlorination.

The high algal productivity of Tenkiller, and the associated production of THM precursors by the algae, was caused by the high P concentration in Tenkiller water, which in turn was caused by the high inflow of P into Tenkiller from the watershed. This has led to a human health risk in drinking water of many residents along Tenkiller's shores. Three of the nine utilities (Cherokee Co. RWD #2, LRED Woodhaven, and Tenkiller Aqua Park) have reported problems with algae to ODEQ (Tenkiller Lake Watershed Survey, 2002).

A five variable model (season, source of water, treatment methods, ecological region of the reservoir, and DOC concentration) was developed to aid in the prediction of the probability of exceeding DBP violation thresholds in tap waters of Quebec, Canada. DOC alone was the most important variable. Based on this model (Milot et al. 2000), the probability of exceeding a THM concentration of 80 µg/L (the USEPA threshold) with a DOC of 2.5 mg/L is 50 percent (using data from Table 4). Using this model, the probability of exceeding the USEPA threshold when treating water from Tenkiller in summer 2006 ranged from 40 percent to 65 percent. Thus, the DOC in Tenkiller surface water was high enough in 2006 to pose substantial and ongoing risks to water supply utilities for producing DBPs, a fact which poses human health risk and the possibility of increased costs to lower the risk. Utilities along the shore of Tenkiller commonly have 30 percent DBP frequencies (Table 1 and Appendix A).

There are other factors, in addition to the P-driven production of algae in Tenkiller, that are involved in an increase in THM formation when eutrophic raw water is used to produce tap water. Photosynthesis by algae, stimulated by increased P concentrations, increases the pH of reservoir surface waters as CO_2 is withdrawn by the cells. The yield of THMs at chlorination increases as the pH of raw water increases (Trussel and Umphres, 1978; Wachter and Andelman, 1984). Utility operators who withdraw water from Tenkiller indicated that they often increase the chlorine dose in an attempt to offset tastes and odors in tap water (telephone interviews between operators and HSWMR Inc). While this treatment may be effective in oxidizing taste and odor molecules, increased chlorine and chlorine contact time in the plant and distribution system will lead to increased THMs in the tap water (El-Dib and Ali, 1994; Graham et al. 1998). Chlorine also breaks up algae cells, releasing DOC, including toxins in blue-green algae cells. Like increased pH, the use of additional chlorine and chlorine contact time to decrease tastes and odors is a direct result of the algal blooms in Tenkiller, which in turn are due to increased P concentrations in the water and thus to increased P loading from the watershed.

The increases in the DBP violations at Tahlequah may be due to plant operation problems, to increases in DBP precursors in the Illinois River, or both. About 26 percent of water samples from Tahlequah were in violation or near violation of the USEPA THM standard (Table 3). Thus more than 18,000 customers experienced excessive and chronic exposure to a known carcinogen in their drinking water.

In summary, a substantial fraction of the drinking water supplied to customers from the treatment of Illinois River and Tenkiller raw water contained DBPs above or nearly above the USEPA thresholds. The production of these DBPs is directly linked to the eutrophication process occurring in these waters, primarily from the disposal of P rich poultry waste on the watershed. A smaller fraction of the P loading to Tenkiller (15.5%) is from the wastewater treatment plants located on the river (Engel, 2008). Reduction of the concentrations of DBPs in the tap waters produced by the utilities requires the reduction of P loading to the river and reservoir (Hoehn et al. 1984; Cooke and Carlson, 1989; Stepzcuk et al. 1998 a, b).

DBPs in tap water are strongly linked to human health risks, including bladder cancer. Villanueva et al. (2006) found a doubling of bladder cancer risk with exposure to DBP levels of 50 µg/L or higher. DBP concentrations of 50 µg/L and higher were commonly found in tap water from the Illinois River and Tenkiller (Table 2, Appendix A). The appearance of molecules linked to human health risks from tap water produced from Illinois River and Tenkiller waters was caused by high P concentrations in the water and the ensuing eutrophication of those waters. Engel (2008) reported that 59 percent of the load of P to Tenkiller was from poultry waste. These conditions violate Oklahoma's water quality standards relating to public and private water supply. The standard requires that waters of the state designated as public or private water supplies (such as the Illinois River, and Lake Tenkiller) be maintained "...so that they will not be toxic, carcinogenic, mutagenic, or teratogenic (OAC 785:45-5-10(5))."

B. Taste and Odor in Tap Water from Tenkiller Reservoir and Illinois River Utilities[2]

The manager or operator of each potable water supply utility on the Illinois River and Tenkiller, except Flint Ridge, was interviewed by telephone (Teaf, 2008). Burnt Cabin, Cherokee Co. RWD #2, Cherokee Co. RWD #13, Pettit Mt., and Tenkiller Aqua Park reported consumer complaints about taste and odor in finished tap water. Each is located on Tenkiller. These complaints indicate a direct violation of Oklahoma Water Quality Standards under "General Narrative Criteria: Taste and Odor" (OAC 785:45-5-9) and Oklahoma's aesthetic water quality standard which states: "The water must be free from noxious odors and tastes (OAC 785:45-5-19)." No other Tenkiller utility reported consumer complaints about taste and odor.

Tastes and odors in finished tap water appeared during summer and fall months. Most of the affected utilities added more alum or activated carbon or chlorine to treat the problem. Utilities with the most severe problems were those located in the upper reservoir (near sample station LK-03; Figure 1) (Teaf, 2008), where eutrophic to hypereutrophic conditions occur during summer months (see Section C, Reservoir Trophic State).

Objectionable tastes and odors often come from two compounds, the alcohols geosmin (trans-1,10-dimethyl-trans 9-decolol) and 2-methylisoborneol (MIB), that are produced by blue-green algae (Cyanobacteria) and bacteria called Actinomycetes (Smith et al. 2002). The threshold concentrations of geosmin and MIB that are detectable by the human palate are exceedingly small (< 30 mg/L; Wnorowski, 1992).

The appearance of taste and odor molecules in tap water is linked directly to increased nutrient concentrations, especially P, that stimulate an increase in algal biomass. Taste and odor problems may linger into fall and winter seasons because geosmin and MIB decay slowly in cold water (Wnorowski, 1992; Pan et al., 2002).

Algae associated with taste and odor episodes are found among the blue-greens, diatoms, dinoflagellates, and greens. Prediction of a taste and odor problem from a species list is difficult because the synthesis of these compounds appears to be confined to specific strains of various species. The presence of a "bloom" of any of the following algae genera is a warning signal to a water supply utility that they may need to begin additional treatments to remove taste and odor. These treatments can be costly (Arruda and Fromm, 1989b; VanBreeman et al., 1991; Wnorowski, 1992).

All of these genera of algae are found in Tenkiller (Appendix B) and all are generally associated with episodes of taste and odor in tap water from various reservoirs:

Oscillatoria (Planktothrix)
Aphanizomenon
Anabaena
Microcystis

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[2] Dr G.D. Cooke is the primary author for this section.

Gloeocystis
Stephanodiscus
Asterionella
Melosira
Cyclotella
Fragilaria
Dinobryon
Scenedesmus
Cryptomonas

Microcystis, Anabaena, and *Oscillatoria* were abundant at all Tenkiller sampling stations and in all years investigated between 1986 and 2007 (see Section C, Reservoir Trophic State).

Another direct indicator of a potential taste and odor problems is lake trophic state, or degree of eutrophication. Arruda and Fromm (1989b) used the chl (chlorophyll; amount of biomass of algae) component of Carlson's Trophic State Index (TSI) (Carlson, 1977) to assess the relationship between trophic state and taste and odor in tap water from some Kansas reservoirs. They found a significant correlation (r = 0.81) between surface water odor and the chl TSI number. Significant odors occurred when the chl TSI number exceeded 45 (a chl concentration 6 µg/L in surface waters). The Carlson Index number increases as a reservoir becomes more eutrophic. Smith et al. (2002) found similar results in Kansas reservoirs.

Mean surface water chl concentrations in Tenkiller at all sampling stations exceeded 6 µg/L in all years except 1974, and at the dam station (LK-01) in 2006. Chl concentrations were most often above 10 µg/L, and at the hypereutrophic station LK-04 in the upper reservoir, average concentration exceeded 20 µg/L. As shown in the Trophic State Section C, high chl (high algae biomass) in Tenkiller is caused by high P concentrations in the water, which in turn are caused by high P concentrations in the inflowing river water. Chl concentrations exceeding a long-term average of 10 µg/L violate Oklahoma Water Quality Standard OAC 785:45-5-10 Public and Private Water Supplies. There are 5 water treatment utilities in the upper reservoir (Figure 3), and consumers of tap water from three of these utilities reported obnoxious taste and odors in their drinking water. However, conditions (presence of problem algae, high P and high chl) existed throughout Tenkiller for taste and odor in tap water (see Section C, Reservoir Trophic State).

Smith et al. (2002) linked blooms of the blue-green algae, *Anabaena* and *Aphanizomenon,* to the presence of geosmin in Cheney Reservoir, Kansas. Chl concentrations of about 10 µg/L were significantly correlated with geosmin concentrations above the taste and odor threshold. This finding supports of results of Arruda and Fromm (1989b). *Anabaena* was a common bloom-forming alga in Tenkiller in all years sampled (Appendix B).

In-plant treatment to remove geosmin and MIB requires oxidants other than chlorine, or the adoption of powdered or granulated activated carbon filtration.

In summary, taste and odor problems are caused by high nutrient concentrations in the reservoir, especially P, that promote "blooms" of algae that can produce geosmin and MIB. Chl concentrations of 10 µg/L or higher, and the presence of common genera of blue-green algae, are strong indicators of an impending taste and odor episode at some point after the bloom develops. Tenkiller had ideal conditions for taste and odor episodes throughout the 10 summers investigated between 1986 and 2007 (see Section C, Reservoir Trophic State).

C. Reservoir Trophic State[3]

Reservoir or lake "trophic state" indicates its amount of biological production. Traditionally, the terms "oligotrophic", "mesotrophic", "eutrophic", and "hypereutrophic" have been used to classify reservoir trophic state. An oligotrophic reservoir has low production of algae, few nuisance Cyanobacteria (blue-green algae), with clear water and usually high concentrations of DO in deeper water. Cool water game fish (e.g. SMB), relatively intolerant to eutrophication, may thrive in such systems. Episodes of taste and odor, DBP problems, and the appearance of toxic algae are uncommon. Eutrophic to hypereutrophic systems have increasing amounts of algae, usually dominated by "blooms" or "scums" of nuisance Cyanobacteria, low water transparency, zero DO in deeper waters, and an abundant fish biomass dominated by more tolerant warm water game species and by rough fish (e.g. common carp) (see Section D, Pattern of Temperature and DO). These more productive water bodies also pose many problems for reservoir users. Mesotrophic water bodies are a transition state between oligotrophic and eutrophic.

The trophic state of a lake or reservoir increases as the concentration of nutrients such as P increases in the system (Hutchinson, 1973; Smolen, undated). Phosphorus is the algal nutrient that often is limiting to algal production. That is, given adequate light and warm water, increasing P concentrations lead to increasing amounts of algae. Conversely, when P concentrations decline significantly, algae production may also decline. In hypereutrophic systems, N or light availability also can be limiting to further algal growth.

The significance of P to eutrophication was intensely investigated in the 1960s and 1970s, worldwide. The debate even extended into the U.S. Congress (Reuss Committee, 1970) before the issue was settled by science. Experiments ranged from laboratory assays, to enrichment of in-lake enclosures with P or N or carbon or combinations of them, to whole lake fertilizations. These studies firmly established P, and sometimes N, as the limiting nutrient (Schindler, 1974; Elser et al. 1990). Indeed, projects wherein P was removed from inflows demonstrated that if P restrictions were large, lakes return to a mesotrophic or oligotrophic condition (see literature reviews in Welch and Jacoby, 2004; Cooke et al. 2005). Extensive data demonstrating the strong correlation between TP and algal biomass (chl) in USA and world-wide lakes and reservoirs have consistently and strongly confirmed the causal relationship between changes in TP concentration and changes in algal biomass (e.g. Jones et al. 1998; Jones and Knowlton, 2005; Watson et al.

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[3] Dr G.D. Cooke is the primary author for this section.

Comparison of Eutrophic Tenkiller with Oligotrophic Broken Bow Reservoir

The degree of eutrophication of Tenkiller can also be assessed by comparing it to unproductive Broken Bow Reservoir (Broken Bow). Broken Bow is located in southeast Oklahoma, in the Ouachita Mountains, about 95 miles from Tenkiller. It receives water from Mountain Fork River.

Broken Bow was sampled for TP and transparency in 1995, 1997, 2001, 2004, and 2006 by OWRB and in 2007 by CDM. Chl samples were taken in 2004 and 2007. The dam sampling station is labeled BBL-01, the deep, open water station as BBL-03, and the upper reservoir station as BBL-08 in Figure 2. Two summer samples were taken in 2001 and 2007, one summer sample in the other years.

Broken Bow was eutrophic in 1997, based on TP and transparency (Figures 17, 19). In other years, it was borderline oligotrophic- mesotrophic, with deeper stations just in the oligotrophic category. Based on chl (Figure 18), Broken Bow was oligotrophic in 2004 and just in the mesotrophic category in 2007. Algae production was P-limited based on the N:P ratio of 19:1 in 2005-2006 (Oklahoma BUMP report 2005 - 2006, p. 67), and on close correspondence to the regression line in Figure 6.

Broken Bow phytoplankton was sampled in 2007. The plankton was dominated by the blue-green algae *Planktothrix limnetica* and *Aphanizomenon ovalisporum*, species not known as nuisance "scum" producers. Their biovolumes were low, as estimated by the 2007 chl (Figure 18).

The low TP concentrations in Broken Bow (Figure 17), with the exception of 1997, are the basis of its high water quality (Oklahoma BUMP Report, 2005-2006, p. 66-70). Broken Bow's low in-reservoir TP concentration occurred because the mean concentration of water entering it (in spring-summer, 2005-2007, 3 year mean, Appendix G) was 27 μg P/L. In contrast, the mean TP concentration in the water entering Tenkiller (in spring-summer, 1997-2006 (except 2002); 9 year mean, Appendix G) was 166 μg P/L, a factor more than 6 times greater than water entering Broken Bow. Annual flow-weighted mean inflow TP to Tenkiller during 2000-2004 was 232 μg P/L (Tortorelli and Pickup, 2006).

The TP concentration in inflowing waters to reservoirs, and ultimately the TP concentration in the reservoir, is correlated with watershed land use. For example, TP and TN concentrations in Missouri reservoirs are negatively correlated with the proportion of forest cover in the watershed (Figure 20; r = - >0.7, n = 126; Jones et al. 2004). Lower P concentrations occur in reservoirs with a higher percent forest cover in the watershed. Forest cover represents watershed areas that are relatively undisturbed, and this relationship between forest cover and nutrients largely explains why inflowing TP concentrations to Broken Bow are much less than in the river inflows to Tenkiller. Figures 21 and 22 illustrate land uses in the watersheds of Broken Bow and Tenkiller. Broken Bow's watershed is 79 percent forested and Tenkiller's watershed is 43 percent forested. Another important difference between the watersheds is that Broken Bow's watershed has about 12 percent of the land cover in grass/pasture while Tenkiller's watershed includes about 45 percent in this cover type (Homer et al. 2004). Grass/pasture is the habitat used for poultry waste disposal.

The disposal of poultry waste on the extensive pastures in the Tenkiller watershed contributes to the large differences in water quality between these two reservoirs (Engel, 2008). Both watersheds have < 1 percent of the land in cultivated crops and runoff from this land use accounts for only a modest amount of nutrient loading to ~~the reservoirs~~. Engel (2008) reported that 59 percent of the TP load to Tenkiller was from poultry waste.

This comparison of Tenkiller with Broken Bow, both P - limited reservoirs (Figure 6), clearly illustrates the causal factor in the eutrophication of Tenkiller Reservoir - the high concentration of TP in the inflowing rivers. These high TP concentrations are the result, in part, of the widespread disposal of poultry waste on the land surface of the Illinois River Watershed. The annual quantity of poultry waste, conservatively estimated as 354,000 tons, coupled with the types of soils and geology of the watershed, assure a significant increase in the TP concentrations in the inflowing waters to Tenkiller (Fisher, 2008). Tenkiller's watershed has 1,917 active poultry houses, in contrast to 248 in Broken Bow's watershed. This is why the concentration of TP in the waters draining into Broken Bow is so much lower than the waters draining into Tenkiller (Fisher, 2008).

The responses of these two reservoirs to the TP loads from their watersheds are summarized in Figure 23 from the Oklahoma 2005-2006 BUMP Report. Broken Bow, with low TP concentrations in its inflows, had high water quality (based on chl), whereas Tenkiller with its much higher incoming TP concentration, had higher turbidity and poorer water quality (Figure 23). It is likely that Tenkiller had, at one time, a trophic state similar to Broken Bow. This conclusion is based on the assumption that the concentration of TP in the inflowing rivers, prior to the removal of forests and the disposal of untreated poultry wastes on the watershed, would be near or below the median concentration of 22 µg/L for streams in undisturbed watersheds of the USA (see Section E, Sedimentation; Omernick, 1977; Clark et al. 2000), and the spring-summer mean TP concentration of 27 µg/L in the Mountain Fork River flowing into Broken Bow.

A computer model (Wells, 2008) indicates that cessation of poultry waste disposal on Tenkiller's watershed will lead to a modest improvement in water quality. Improvement will not be rapid because soil test phosphorus in the watershed is high due to poultry waste disposal, and TP will continue to flush into the river and then into Tenkiller from those soils for many years (Engel, 2008). Because the model is based upon a 10 year cycle of high, medium, and low water years that duplicates the actual weather and runoff patterns at Tenkiller, the model shows that there will be years of higher and lower TP and chl concentrations, with an overall downward pattern following cessation of poultry waste disposal on the land (Wells, 2008). At the end of a 50 year period, the trophic states of LK-01 and LK-02 will become meso-oligotrophic, whereas LK-03 and LK-04 will become meso-eutrophic. The likely effect will be a modest drop in the risk of algal blooms, including blue-greens, and the associated problems with DBPs, taste and odor, algal toxins, and water transparency. Recycling of the TP that has accumulated in reservoir sediments over the years of poultry waste disposal, especially at LK-04 and LK-03, may delay reservoir recovery.

The model (Wells, 2008) also predicts that trophic state at LK-01 and LK-02 will become highly eutrophic (TP-TSI values of 60-65; Table 7 of this report for trophic state boundaries) by the end of the 50 year period if poultry waste disposal on the land of the watershed continues and grows at the current rate (Engel, 2008). Under that growth scenario, conditions at LK-03 and LK-04 will become very hypereutrophic (TP-TSI values of 70-80). These TP-TSI values were computed by using the projected percent increase in TP concentrations at the four reservoir stations at the end of the 50 year modeling period (see Tables 31 and 32; Wells, 2008) and Carlson's (1977) TP-TSI equation (p. 21, this report). Eutrophic and hypereutrophic states in Tenkiller would lead to large, entire-summer algal blooms, particularly blue-green algae, severely impacted potable water and associated human health risks from DBPs and algal toxins, greatly impaired recreational and aesthetic conditions (e.g. transparency less than 0.5 meters/1.5 feet), and worsened habitat quality for sensitive fish species such as smallmouth bass (see Section D). It is very difficult and expensive to rehabilitate a reservoir that has deteriorated to eutrophic/hypereutrophic states (Cooke et al. 2005).

D. Pattern of Temperature and DO and Effects on Aquatic Life[4]

(Appendix E contains the data used to characterize temperature and DO conditions.)

Reservoirs usually differ markedly from lakes due largely to their narrow, longitudinal shape and their higher watershed area-to-reservoir volume ratio. These physical differences result in higher water inflow rates and consequently lower water residence times, as well as a longitudinal zonation effect that produces a sequence of riverine, transition and lacustrine-type features (Thornton, et al., 1990). Reservoir inflows tend to plunge in the transition zone entering the lacustrine zone as an interflow or density current. The higher density is due to a combination of lower temperature, and higher conductivity and suspended solids, especially during summer when the lacustrine zone is thermally (density) stratified (Thornton et al., 1990). Stratification in the lacustrine results in a surface mixed layer (epilimnion), intermediate depth transition layer (metalimnion) and bottom layer (hypolimnion).

The density current tends to enter the lacustrine zone in the intermediate layer (metalimnion), producing metalimnetic DO minima (Thornton et al., 1990). Reservoirs with residence times less than one year tend to have pronounced interflows (Straskraba, 1999). This pattern is evident in Tenkiller, which had a mean residence time of 1.2 HYs (April-September) during 2000-2007. Thermal stratification in the lacustrine zone produced a mixed epilimnion (Figure 24). This layer extended from surface to about 6 m in early summer, to about 12 m in late summer in 2005, as wind action eroded the thermocline (Figure 24). The pattern was similar in 2006 and 2007 (Figures 25 and 26). DO depletion was greater in the metalimnion than the hypolimnion during June - July; thus, DO reached levels < 1 mg/L much sooner than in the hypolimnion, a condition that is common in reservoirs but is atypical in lakes (Figures 24, 25, and 26). By August, however, DO was depleted from about 8 m throughout the water column to the bottom.

Conductivity profiles indicated slightly higher metalimnetic density during the June - July period, consistent with higher conductivity in the riverine zone (Figure 24). River conductivity averaged 303 µS/cm during spring-summer compared to epilimnetic

[4] Dr E.B. Welch is the primary author of this section.

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values always < 200 µS/cm and declining throughout the summer, while values increased in the hypolimnion in late summer (Figure 24). This indicates that the interflow entered the metalimnion in early summer and then spread to the hypolimnion in late summer consistent with less dilution of higher conductivity base flow in late summer. Suspended solids levels were also higher (transparencies much lower) in the riverine section, which would have contributed to the inflow's greater density. These characteristics of the inflow, along with a slightly lower river temperature than the reservoir surface, allowed the inflow to move into the metalimnion and hypolimnion, and not mix with the lacustrine epilimnion. The pattern was similar in 2006, although conductivity was slightly higher with a steeper gradient through the water column (Figure 25).

Therefore, most of the high riverine zone TP, causing the high algal biomass there, did not reach the lacustrine epilimnion. Instead, a large fraction was deposited in the transition zone (station LK-03, Figure 27). Retention of TP in the riverine zone was only about 15 percent, compared to about 80 percent in the transition zone (Figure 27). The decrease in TP between the transition zone and the lacustrine zone epilimnion resulted partly from continued sedimentation and transport to the metalimnion and hypolimnion with the interflow.

TP was further lost from the hypolimnion in the lucustrine zone through the 37 m deep dam outlet. This loss is demonstrated by lower hypolimnetic TP at lacustrine station LK-01 (near the dam) than at station LK-02 (Figure 28). While hypolimnia of both zones were equally anoxic (average AF for 2005 and 2006 ~ 90 days), the observed P release rates were 13 and 5 times greater at station LK-02 than at station LK-01 for 2005 and 2006, respectively (Figure 28). That difference was probably due to TP loss from the hypolimnion of station LK-01 through the dam outlet. That is, release of P from anoxic sediment at station LK-01 was not able to accumulate in the overlying water as it did at station LK-02. While the anoxic period was similar in the two zones, and actual P release rate was probably similar, the hypolimnetic residence time was probably shorter at station LK-01 due to the outlet flow.

As a result of sedimentation and interflow transport, the lacustrine epilimnion was essentially protected from inflow TP and maintained a mesotrophic state despite hypereutrophy in the riverine zone and eutrophy in the transition zone (see Section C, Reservoir Trophic State). However, algal organic matter produced in the riverine and transition zones probably contributed to DO depletion in the lacustrine meta and hypolimnia. The contribution of reservoir derived organic matter (algae) is indicated by higher content of TOC in the reservoir (2.5-3.0 mg/L) than in the river (1.5 mg/L) (see Section A, Disinfection-By-Products; Olsen, 2008).

DO Depletion Indicators

Areal hypolimnetic oxygen deficit (AHOD) is calculated as the rate of depletion in volume-weighted DO in the hypolimnion, prior to minimum DO reaching 2 mg/L. This index gives the rate of removal of DO by DO demanding organic materials entering the hypolimnion. AHOD averaged 1,329 mg/m² per day in the lacustrine zones (stations

LK-01 and LK-02) of Tenkiller during the summers of 2005 and 2006 with a maximum of 2,094 mg/m^2 per day (Figure 29). That is a very high rate and far exceeded the hypereutrophic boundary for lakes (550 mg/m^2 per day; Nurnberg, 1996). Moreover, the 2005-2006 mean exceeds the maximum rates from 149 lakes and reservoirs reported by Walker (1979 and 1987).

There is some uncertainty in the computation of AHODs that depends on the completeness of data sets. For example, there is an 18 percent difference between the two sets of 2005 data relative to that mean. No trend is evident over the years of available data. Moreover, AHODs were not higher in years with long residence times than in years with short residence times, although DO depletion has been shown to be greater in reservoirs with long residence times (Straskraba, 1999). Lack of a trend or effect of residence time may be partly due to computation uncertainty if differences were relatively small.

Walker (1987) calculated AHODs for Tenkiller of 1,222 mg/m^2 per day for 1986 and 818 mg/m^2 per day for 1974, which were related to mean chl concentrations of 18 and 7 µg/L, respectively, in his regression of AHOD on chl. Those AHOD rates are within 5 and 13 percent of the mean rates calculated using the DO data sources for those years (Figure 29). While Walker interpreted these two values as a trend, the larger data set reported here does not indicate a trend. In some, there is as much difference between stations in one year and between successive years as Walker observed between 1974 and 1986 (Figure 29).

Reservoirs usually have greater hypolimnetic DO depletion rates (AHODs) than lakes, probably because of their relatively greater watershed area to lake volume ratios and, hence, higher inflows that produce interflows carrying watershed derived organic matter to the metalimnion and hypolimnion. The difference in AHODs between lakes and reservoirs can be illustrated using Walker's (1987) equation for AHOD regressed on chl for reservoirs ($n = 37$, $r^2 = 0.65$) and the mean chl (9.3 µg/L) at lacustrine stations LK-01 and LK-02 during 2005-2006. That prediction yields an AHOD of 843 mg/m^2 per day, while that chl (9.3 µg/L) and Walker's equation for lakes ($n = 31$, $r^2 = 0.66$), predicts 597 mg/m^2 per day, about 30 percent less than for reservoirs. That difference may be due to the greater watershed area-to-volume ratio and interflow effect in reservoirs, as mentioned above.

Another source of organic matter in reservoirs is the greater algal production that typically occurs in reservoir riverine and transition zones (see Section C, Reservoir Trophic State). As indicated earlier, biomass produced there tends to settle and not enter the lacustrine zone epilimnion. However, that biomass would ultimately be part of the DO demand exerted in the meta and hypolimnion of the lacustrine zone through either sediment demand on overlying interflow water or demand in the water itself. With that process in mind, Walker's equation for chl versus AHOD may be used with the riverine and transition zone observed chl (21 µg/L) in Tenkiller to predict lacustrine AHOD during 2005 and 2006. That prediction yields an AHOD of 1,216 mg/m^2 per day, which is nearly as high as that observed (1,329 mg/m^2 per day).

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For contrast, Broken Bow is an eastern Oklahoma reservoir that is oligo-mesotrophic (see Section C, Reservoir Trophic State) and in which DO remains well above anoxic levels (< 1-2 mg/L), except very near the bottom and at the end of the stratified period (Figure 30). Consequently, the AHODs in Broken Bow are much lower than in Tenkiller – mean of 531 mg/m² per day for 2001 and 2004 (the only years with adequate data; Figure 29). The reason Broken Bow is oligo-mesotrophic with a lower AHOD is that spring-summer mean inflow TP concentration is low (27 µg/L in 2005-2007, Appendix G), relative to Tenkiller (161 µg/L in 2006, Figure 27; 166µg/L in 1997-2006 (except 2002)).

The above inflow concentrations to Tenkiller and Broken Bow are interesting with regard to the Oklahoma water quality standard for aesthetics (OAC 785:45-5-19) of 37 µg/L as a geometric mean (GM). The range in spring-summer GM into Broken Bow from Mountain Fork River during 2005-2007 was 24-33 µg/L and into Tenkiller via the Illinois River, its major tributary, at Tahlequah during spring-summer 1997-2006 (except 2002) was 68-247 µg/L. Hence, oligo-mesotrophic Broken Bow received spring-summer inflow TP that was 4-13 µg/L less than the standard while Tenkiller's major inflow was 2-7 times greater than the standard. An examination of TP data from other scenic river segments throughout the Illinois River Watershed of the GM TP compared to the 37 µ/L standard was performed by Brian Bennett of CDM and Robert Van Waasbergen of Applied Environmental Data Services, as follows.

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The available TP data for each stream segment that has been designated as a Scenic River within the Illinois River Watershed has been analyzed using 30-day rolling GMs and 3-month rolling GMs as described in OAC 785:45 and 785:46. A summary of the number and percent of monthly determinations in which the GM TP concentration exceeds the 0.037 mg/L (37 µg/L) standard for aesthetics in designated Scenic Rivers is also provided in the tables for each stream segment in Appendix H. Also, a figure in Appendix H shows the scenic river segments and sampling locations.

The 30-day GM of TP concentrations exceeded the 37 µg/L standard for samples collected in the Illinois River above the confluence with the Baron Fork in 103 of 122 (84%) determinations for stream segment 121700030010, in 66 of 68 (97%) determinations for segment 121700030080, in 11 of 11 (100%) determinations for segment 121700030280, and in 90 of 91 (98.9%) determinations for segment 121700030350 (Appendix H). For samples collected from the Baron Fork from the mouth upstream to Oklahoma HWY 59, the 30-day GM of TP concentrations exceeded the 37 µg/L standard in 27 of 112 (24%) determinations for segment 121700050010 and in 5 of 5 (100%) of determinations for segment 121700050170 (Appendix H). For samples collected from Flint Creek, the 30-day GM of TP concentrations exceeded the 37 µg/L standard in 14 of 14 (100%) and 164 of 164 (100%) determinations for stream segments 121700030290 and 121700060010, respectively (Appendix H).

When a 3-month rolling GM is calculated for the same data collected from the Illinois River above the confluence with the Baron Fork, the 37 µg/L standard is exceeded in 51 of 57 (89.5%) determinations for stream segment 121700030010, in 23 of 24 (95.8%) of determinations for segment 121700030080, in 1 of 1 (100%) of determinations for segment 121700030280, and in 43 of 43 (100%) of determinations for segment 121700030350 (Appendix H). For the Baron Fork from the mouth to HWY 59, the 37 µg/L standard was exceeded in 20 of 61 (32.8%) of 3-month rolling GM determinations for stream segment 121700050010 and in 8 of 8 (100%) of determinations for segment 121700050170 (Appendix H). Among samples collected from Flint Creek, the 3-month rolling GM of TP concentrations exceeded the 37 µg/L standard in 19 of 19 (100%) and 55 of 55 (100%) of determinations at segments 121700030290 and 121700060010, respectively (Appendix H).

The available TP data for each stream segment has been analyzed by the OWRB using 3-month rolling GMs as described in OAC 785:46. A summary of the number and percent of determinations in which the GM TP concentration exceeds the 37 µg/L standard for aesthetics in designated Scenic Rivers is also provided in the tables for each stream segment in Appendix I.

The 3-month rolling GM of TP concentrations exceeded the 37 µg/L standard for samples collected in the Illinois River at Tahlequah, OK in 50 of 53 (94%) determinations (Appendix I). At the Illinois River near Watts, OK the 3-month rolling GM exceeded the 37 µg/L standard in 53 of 53 (100%) of determinations (Appendix I). The Baron Fork near Eldon, OK had 3-month GMs in exceedence of the standard in 16 of 54 (30%) of determinations (Appendix I). The 3-month rolling GM of TP concentrations exceeded the 37 µg/L standard for samples collected from Flint Creek near Kansas, OK in 54 of 54 (100%) of determinations (Appendix I).

Anoxic Factor (AF) is another DO indicator that is directly related to TP. The AF in the Tenkiller lacustrine zone (stations LK-01 and LK-02) during 2005 and 2006 averaged 91 days. AF is the time a lake bottom area equivalent to the lake surface area was ≤ 2 mg/L DO during the stratified period. The 2005-2006 average AF for Tenkiller exceeds the hypereutrophic boundary of 60 days (Nurnberg, 1996) and all values for 75 lakes reported by Nurnberg (1995). By contrast, AF in Broken Bow was estimated to be very short, because DO in the hypolimnion at the near dam lacustrine sites did not go anoxic until the end of the stratified period. Also for most of the stratified period, DO was > 4 mg/L throughout the hypolimnion (> 18 m, Figure 30). gew

Effect of DO/Temperature on Fish Habitat

Low DO is the principal factor that adversely affects fish species intolerant of eutrophication. The decreased meta and hypolimnetic DO, and the increasing epilimnetic temperature, during the summer stratified period effectively "squeezes" the habitat volume available for survival and growth for some important endemic and introduced game fish.

The endemic sport/game fish species in Tenkiller, intolerant to this effect of eutrophication, are SMB (Figure 30a), spotted bass and channel catfish. Striped bass and walleye (Figure 30a), also intolerant of eutrophication, were introduced to Tenkiller in large numbers to establish viable populations. For these intolerant endemic species, the minimum DO and maximum temperature criteria for optimum growth are 6 mg/L and

27° C, while 5 mg/L and 29° C are considered suboptimal for growth (Table 11). Even lower temperatures were recommended for successful introduction of SMB to Kentucky reservoirs; 21-23° C as acceptable and 20-21° C as ideal (Buynak et al., 1991). These temperature limits for growth of SMB (27-29° C) are too high for introduced striped bass and walleye, because those species avoid temperatures above 24° C, seeking lower preferred temperatures (21-22° C, Table 11). Fish prefer temperatures that are optimum for growth and activity and avoid higher temperatures (Beitinger and Fitzpatrick, 1979).

A DO of 5 mg/L is suboptimum for growth of all these species, but it will allow some growth, and survival is possible down to 2-3 mg/L. Even largemouth bass (LMB), considered more tolerant of eutrophication than SMB, showed decreased food consumption and growth at DO concentrations less than saturation (9.2 mg/L @ 20° C; Stewart et al., 1967). Reduced fry survival and feeding have been other suboptimal effects (Table 11). However, these criteria (5-6 mg/L) serve to show the stress to sensitive fish that occur in Tenkiller during the summer, stratified period. These DO criteria are consistent with limits set by OWRB for cool and warm water species during summer (Table 1 in OAC 785:45-5-12).

As an indication of stress to the fish species in Tenkiller, the calculated mean hypoxic factor (HF) for a DO of 5 mg/L averaged 107 days at the two lacustrine stations in 2005 and 2006. That means DO in Tenkiller was ≤ 5 mg/L below an area equivalent to the lacustrine surface area for 107 days during the stratified period. That further means that a very large volume of the lake is < 5 mg/L during summer. Although data were inadequate to calculate HF for meso-oligotrophic Broken Bow, its index value would be smaller than for Tenkiller, because metalimnetic DO declined slower than in Tenkiller. Also, hypolimnetic DO in Broken Bow was near to or exceeded 5 mg/L for most of the stratified period (Figure 30), which provided a refuge despite low metalimnetic DO levels.

<u>Fish Response to Habitat Squeeze</u>

Smallmouth and spotted bass were abundant in the Illinois River prior to the existence of Tenkiller. Moreover, the rich fauna present in the river was considered sufficient to naturally populate the reservoir without stocking (Moore and Paden, 1950). However, catch rates for SMB, based on OK Dept. of Wildlife Conservation (ODWC) data, have been very low over the last 30 years, and well below that regarded by ODWC as a quality fishery. That is despite 100,000 being stocked in Tenkiller during the 1990s (Figure 31). While electrofishing catch rates appear to have increased in recent years, there is too much uncertainty from year-to-year or over time to evaluate trends. Nevertheless, the data do reliably depict differences between Tenkiller and Broken Bow fisheries.

Catch rates for SMB in Broken Bow have been much higher than in Tenkiller and reached the quality fishery level (10/hour) in 1998 and 2002 and nearly so in 2001 and 2004 (Figure 31). About 250,000 SMB were stocked in Broken Bow in the 1970s-1980s (ODWC, personal communication). While SMB have not consistently achieved a quality fishery rating over the years, catch per unit effort (cpue) has been consistently greater in

Broken Bow with a long-term average of 4.4/cpue versus 1.4/cpue for Tenkiller (significant at 0.05 level).

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While possible differences in physical habitat, prey availability, and interspecific competition may partly explain the poorer success of SMB in Tenkiller, the greater habitat squeeze must be considered an important cause for the difference in catch rates. Actually, the lower catch rates in Tenkiller occurred despite a greater food productivity provided by the reservoir's eutrophic state. However, as reviewed in the Introduction, SMB prefer mesotrophic to oligotrophic conditions, largely due to DO constraints in eutrophic waters. The greater AHODs, AFs and HFs for Tenkiller than Broken Bow are evidence of the markedly different DO regimes. Using the criteria discussed above for optimum (< 27° C and > 6 mg/L DO) and suboptimum (< 29° C and > 5 mg/L DO) conditions for growth of SMB, there was little or no favorable habitat available for growth or even a refuge in Tenkiller during most of the stratified period in summer 2006 (Figures 32 and 33). Data for 2005 and 2007 show essentially the same pattern.

The volume with these temperature/DO limits also illustrates available habitat existing in Tenkiller during the stratified period (Figure 34). Optimum conditions were largely unavailable for three months during 2005 to 2006 – an average of only 4 percent of the lake volume during 6/15 – 9/20/05 and 16 percent during 6/27 - 9/14/06. Data were insufficient to define the period in 2007. Suboptimal conditions were available in more of the volume – 21 percent and 29 percent for the respective periods in 2005 and 2006. This means that SMB are probably restricted to a very small portion of Tenkiller that may result in other effects such as food limitation and crowding. This restriction of space is also emphasized in OWRB water quality standards with "screening level for DO in lakes" (OAC 785:46-15-5). They state that fish and wildlife beneficial use is not supported if the fraction of the water column with < 2 mg/L DO exceeds 70 percent if not naturally occurring, and that criterion is exceeded in Tenkiller (Figures 24-26).

One might ask how SMB survive at all with so little acceptable habitat available for most of the summer. These criteria are optimal and suboptimal (marginal) for growth. Temperature was often near but did not exceed the lethal limit of 32° C in the surface water (0 - 6m) with sufficient DO during 2005 - 2006, so outright lethal conditions did not occur and survival was possible in the epilimnion (Table 11). However, temperatures > 27-29° C are avoided by SMB and are not conducive to growth (Table 11). An exception was an artificial stream experiment in which SMB were shown to survive and grow with natural food production at mean weekly temperatures raised from a background of about 28° C during July and August to about 33° C (Wrenn, 1980). Nevertheless, in all other experimental and observational results, temperatures > 27-29° C are avoided by SMB and are, therefore, not considered optimum for growth (Table 11).

In contrast to Tenkiller, SMB were not nearly as restricted by temperature and DO in Broken Bow. Much of the hypolimnion had sufficient DO to serve as a refuge from sub-optimal epilimnetic summer temperatures of 30 - 32° C (Figures 35 and 36). The more favorable temperature and DO habitat is considered at least a partial cause for the much greater success of SMB in Broken Bow and catch per effort coming closer to a quality level than is the case for Tenkiller. There were insufficient data from Broken Bow to compute acceptable habitat volumes during an entire stratified period. However, the water column fraction that is < 2 mg/L DO in Broken Bow was much less than the 70 percent criterion (Figure 30).

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Largemouth bass are considered more tolerant of increased temperature than SMB and even thrive in mildly eutrophic waters (Table 11; Ludsin et al., 2001; Maceina and Bayne, 2001; Greene and Maceina, 2000). Over a third of a million LMB were stocked in Tenkiller and nearly 2.5 million in Broken Bow over the life of the reservoirs (ODWC, personal communication). As would be expected, the catch per effort in Tenkiller (mean 88/cpue), has been greater (significant at 0.005 level) than Broken Bow (mean 46/cpue), although both means exceed the quality fishery level of 40/cpue determined by ODWC (personal communication).

Spotted bass have been much more successful in Tenkiller than SMB. The average catch per effort has been 18/cpue versus 1.4/cpue for SMB. Unfortunately, there are no catch records from Broken Bow, so a comparison of relative success in the two reservoirs is not possible. However, spotted bass are apparently intermediate between LMB and SMB in their response to eutrophication. While spotted bass were more abundant and grew faster in eutrophic reservoirs (chl > 8 µg/L), they were also much more abundant and grew faster in the mesotrophic and oligotrophic (3-4 µg/L chl) than LMB (Greene and Maceina, 2000). In a reservoir that underwent oligotrophication, spotted bass became more successful than LMB (Maceina and Bayne, 2001).

Much effort was expended to establish walleye and striped bass fisheries in Tenkiller and walleye in Broken Bow. Over 14 million walleye were stocked in Tenkiller from 1954 to 1998 and nearly 9 million in Broken Bow in the early 1990s (ODWC, personal communication). Nearly a million striped bass were stocked in Tenkiller in the 1970s and 1980s. However, none were stocked in Broken Bow.

Despite this stocking effort, walleye catch per effort has remained very low and they are considered uncommon in Tenkiller, while the population is self sustaining in Broken Bow with a catch per effort 3.5 times greater (significant at the 0.005 level) than in Tenkiller (Figure 37). The greater success of walleye in Broken Bow is consistent with more acceptable DO/temperature habitat available during summer (Figure 38) than in Tenkiller (Figure 39). Stocking of striped bass in Tenkiller failed to establish a fishery (ODWC, personal communication).

The habitat squeeze for walleye and striped bass in Tenkiller is illustrated for suboptimal conditions (> 5 mg/L and < 24° C) in Figure 34. There was no volume of acceptable habitat available for these taxa from 6/29 to 10/4 in 2005 and < 1 percent of the volume was acceptable habitat from 6/12 to 9/14 in 2006. Such a severe squeeze has explained the failure of striped bass populations in South Carolina reservoirs (Coutant, 1985 and 1987). Given the similar DO and temperature requirements of the two taxa (Table 11), one can conclude that this phenomenon was a major cause for failure of walleye and striped bass in Tenkiller. That is especially evident from the success of walleye in Broken Bow, in which such a severe habitat squeeze is absent.

EBW

The DO/temperature habitat that probably has lead to poorer success of SMB and walleye in Tenkiller than in Broken Bow and failure of striped bass in Tenkiller is not expected to change appreciably soon by the cessation of poultry waste application in the watershed. Although model simulation predicts a nearly two-fold increase (1.6 to 2.9 mg/L) in the May-October average DO in the outlet from the hypolimnion of Tenkiller during a 50-year period, only a modest increase (28-13%) in optimal and suboptimal habitat volume for SMB would be expected during June 15 to September 15. Habitat for walleye would double, but actual volume still would be small (3.5%; Wells, 2008). This predicted slow and incomplete response of DO to reduced TP loading may be related to the high sensitivity of DO depletion rate in reservoirs to eutrophication as discussed previously; i.e., reservoirs tend to have higher AHODs than lakes.

Nevertheless, the DO regime in Tenkiller does respond to a substantial decrease in TP loading, according to the model. Model simulation indicates that average May-October outlet DO over 50-years would have been four-fold higher without TP loading from poultry and domestic waste (i.e., assumed natural inflow of 20 µg/L - see section E, Sedimenation; Wells, 2008). Thus, May-October outlet DO from Tenkiller currently would be similar to that at depth in Broken Bow (~ 6 mg/L, Figure 30) if the inflow TP to Tenkiller over 50 years had been similar to that to Broken Bow, which was 27 µg/L during spring-summer, 2005-2007 (appendix G). Increase in volume of optimal and suboptimal habitat for growth of SMB would have been 1.7-2.8-fold greater under the natural scenario. Walleye habitat would have increased nearly ten fold, but percent of total volume still would have been small - 14 percent (Wells, 2008).

The outlet DO increase would have been 2.5 fold higher had TP loading remained at a historic level of poultry and domestic waste at the time of dam closure (Wells, 2008). However, habitat volume would have differed little from present at the historic loading levels. If poultry waste application were to continue to increase at the current rate (Engel, 2008), neither outlet DO or critical period habitat volume for these sensitive fish species would change over 50 years, as predicted by the model (Wells, 2008). Essentially, the near worst-case DO/temperature habitat condition would prevail.

These model predictions are reasonable considering that measured optimal and suboptimal habitat volumes for SMB averaged 10 and 25 percent in 2005-2006 and the current TP loading base case predictions were 8.5 and 33.5 percent, respectively.

Benthic Macroinvertebrates

The density (abundance/area) of macroinvertebrates at four sites in Broken Bow (1,027/m^2) was over six-fold greater than in Tenkiller (150/m^2). Both reservoirs were sampled in November 2007 (Table 12). The greatest abundance in reservoirs usually occurs in late fall and winter, so densities were probably at or near maximums at sampling times (Craven and Brown, 1969).

The average density in Broken Bow (1,027/m^2) is well within the range observed in shallow, productive reservoirs in which DO did not reach anoxic conditions (Craven and Brown, 1969; Popp and Hoagland, 1995; Peterka, 1972; and Ferraris and Wilhm, EB&W

1977). Oligochaete worms represented much of the abundance in both reservoirs, while the phantom midge, *Chaoborus*, was equally as abundant as oligochaetes in Tenkiller and half as abundant in Broken Bow (Table 12).

Oligochaetes usually form an increasing proportion of total abundance with increasing eutrophication (Bazzanti and Seminara, 1985; Popp and Hoagland, 1995). Some chironomids (midges) also tolerate eutrophic conditions, capitalizing on the increased organic matter food supply, while resisting low DO (Welch and Jacoby, 2004). Although present, chironomids were not major contributors to abundance in either reservoir.

An increasingly uniform fine-sediment substrata is also an important factor in the increasing importance of worms and midges as reservoirs age (Popp and Hoagland, 1995). Oligochaetes comprised an increasing fraction of the biomass with depth in eutrophic Lake Washington (although DO was > 2 mg/L), while chironomids (100-200/m^2) maintained a constant dominance with depth in oligotrophic Cree Lake, Canada (Welch and Jacoby, 2004). Despite the eutrophic state of Tenkiller, chironomids, *Chaoborus* and even oligochaetes were very low in abundance in Tenkiller. In contrast, abundance levels of *Chaoborus* and oligochaetes were about what one would expect for an oligo-mesotrophic reservoir such as Broken Bow (Table 12). The difference in DO regimes in the two reservoirs at least partly explains the low abundance of organisms in Tenkiller. While these organisms can resist low DO for a month or so and still survive, they are not able to grow under anoxic conditions as occurred for at least three months per year in Tenkiller. For example, the AF, for ≤ 2 mg/L in water overlying sediment, averaged 91 days in Tenkiller, but DO in Broken Bow was well above 2 mg/L for the whole summer period. Therefore, aquatic life in Tenkiller exhibits degraded conditions, compared to a regional water body of similar size and flow, which violates the biological criteria in OWRB water quality standards (OAC 785: 45-5-12).

E. Sedimentation[5]

(Appendix F contains the sediment core data used in this section.)

Sediment core data were used to estimate sedimentation and P deposition rates over time in Tenkiller. Documenting lake history related to eutrophication and other sedimentation processes by dating sediment cores with Pb^{210} and other time markers is common practice in limnology (Engstrom and Wright, 1984). Changing P content with time has been related to increased and decreased rates of P loading over time (Shapiro et al., 1971; Birch et al., 1980; Engstrom, 2005; Birch 1976).

Reservoirs tend to fill in with sediment, but usually much faster than the time scale of hundreds to thousands of years required to fill lakes. Reservoirs can lose one-fourth to one-half their volume in ~ 50 years (Holz et al., 1997). However, Tenkiller has behaved more like a lake with sedimentation rates in the lower three lacustrine zones (Figure 1, blue and green areas) at 0.8 to 1.1 cm/year and in the transition zone at 1.7 cm/year (Figure 1). Over the 53 years of reservoir life, only about 0.5 m of the 19.7 m lacustrine mean depth, or 2.5%, has been lost to filling. Sedimentation rates in lakes are usually less

[5] Dr E.B. Welch is the primary author of this section.